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Quantum Dot Energy Harvesters for Powering Implantable Medical Devices

Abstract

Presently, electronic medical implants such as pacemakers, defibrillators, and neurostimulators rely on batteries that require constant surgical replacement. In the future, a convenient and permanent solution will harvest the thermal energy of the human body through a simple heat engine made from quantum dots. QDs are nanocrystals that exhibit special properties, namely their ability to easily morph into efficient semiconductors, which will revolutionize thermoelectric generators and supercapacitors. Heat engines made with QDs have high efficiencies because of their chemical potential energy, yielding high energy densities and power outputs. Our Quantum BioEngine system will generate energy through temperature gradients of the body using a solid state chip implanted subcutaneously. As medical devices use less energy, self-powered implants will be commonplace and integrated into diagnostic apps for cell phones. The convergence of quantum dot technology with biomedical devices will create a world where human power sustains human life.

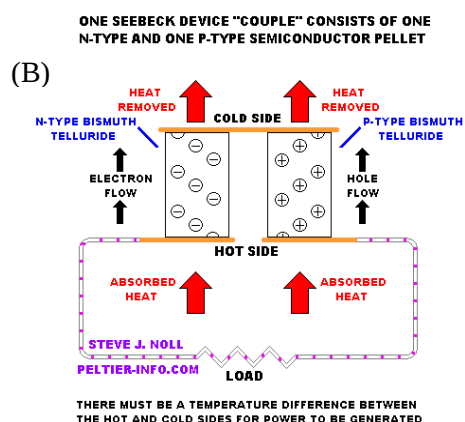
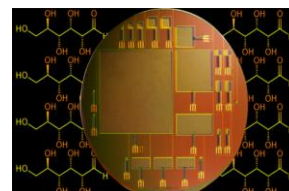
Quantum Dot Energy Harvesters for Powering Implantable Medical Devices

Present Technology

Current biomedical implants include left ventricular assist devices (LVADs), pacemakers, implantable cardiovascular defibrillators (ICDs), electrocardiogram (ECG) amplifiers, and neurostimulators. Most of these devices receive power from an internal source, generally non-rechargeable lithium batteries. These batteries are impermanent and need to be replaced after a set period of time, meaning that these internal implants still require invasive maintenance and are not self-sufficient.

To replace outdated battery technology, several methods of generating power for medical devices exist. These include kinetic energy generators, glucose energy harvesters, and external inductive power sources. Kinetic energy generators require mechanical movement of the human body to shake a magnet back and forth within a coil. Glucose energy harvesting uses fuel cells to convert glucose within the human body into electrical energy. It relies on the chemical reaction of oxygen and glucose, generally using enzymes to facilitate electron movement. Charging batteries using induction is efficient but can be impractical, in that a charging device may not be

(A)



available—the process still relies on chemical batteries that would have to be replaced.

Our project relies on the thermoelectric effect to generate power. In this process, two dissimilar metals produce electricity when heated. Currently, the most efficient thermoelectric generator is a PN junction, as shown in the figure at

left. When a temperature difference forms on either side of the metal plates, the electrons in the semiconductor material become excited, creating a voltage. This process, the Seebeck effect, can also be used in reverse, by sending a voltage between two plates to create a temperature differential. This device is called a Peltier cooler, a solid state heat engine operating between two different temperatures. Carnot showed theoretically that the efficiency of both Peltier coolers and thermoelectric engines can never exceed the ideal efficiency, which he formulated as such:

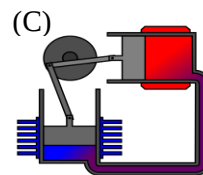
$$\eta = \frac{W}{Q_H} = 1 - \frac{T_C}{T_H}$$

The human body temperature is 310 K and varies by approximately 3 K, making T_C 307 K and T_H 310 K. In an ideal situation, these conditions would yield an efficiency of 1%. It seems implausible that this Carnot heat engine would work inside the human body. However, researchers at the University of Rochester have proposed a quantum dot thermal energy harvester with a much higher efficiency.

A quantum dot (QD) is a finely-tuned semiconducting nanocrystal. QDs can be engineered to have discrete energy levels similar to electron orbitals around atoms. Their sizes can range from 9nm to 2nm. Their ability to be tuned allows for efficient energy transfer in a heat engine. QDs can also be used to improve the storage capacity of energy in supercapacitors. In particular, researchers have shown that graphene semiconductors made from QDs have high energy densities. Currently, the best supercapacitors have specific energy densities, ranging from 1-30 watt hours per kilogram, approximately $\frac{1}{5}$ the energy of a comparable lithium ion battery. There are no self-sustainable bioengines that currently exist—researchers are now examining the possibility of integrating QDs and thermoelectric engines to achieve higher energy efficiencies and electrical outputs.

History

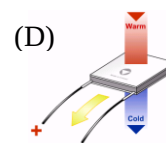
1816: Robert Stirling, a Scottish inventor, patents the Stirling Engine—a closed cycle air engine that operates by the heating and cooling of a gas.



1821: Thomas J. Seebeck, a German physicist, discovers that current will flow between wires that separate junctions of two different temperatures (Seebeck effect).

1824: Nicolas Leonard Sadi Carnot proposes a theory (Carnot's Theory) on thermoelectric engines that the ideal efficiency of these engines is: $\eta_{\max} = \eta_{\text{Carnot}} = 1 - \frac{T_C}{T_H}$

1834: Jean Peltier discovers the opposite of the Seebeck effect is also true, that a current can cause a temperature difference.

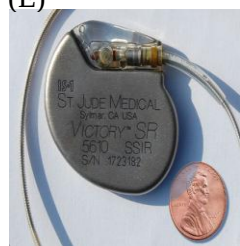


1947: The theory of graphene, a 1-atom-thick layer of graphite, is explored by P.R. Wallace. Scientists today are using graphene in QD research.

1957: Howard Becker discovers the first supercapacitor but does not understand it.

1958: The first implantation of a pacemaker into a human occurs in Sweden. Designed by Rune Elmqvist and Åke Senning, the first pacemaker lasts just three hours before failing.

(E)



1972: The first pacemaker with a lithium ion battery is implanted.

1980: The first cardioverter-defibrillator is implanted in a patient.

1988: The first artificial LVAD is successfully implanted long-term.

1980s: QDs are discovered in a glass matrix by Alexei Ekimov and in

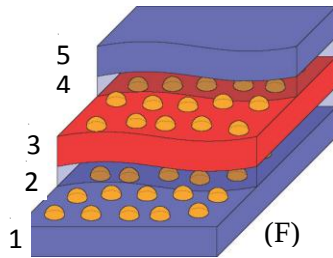
colloidal solutions by Louis E. Brus. QDs can be tuned to precise frequencies during synthesis.

Their conductive properties are also extremely controllable.

2013: An efficient thermoelectric engine using QDs is proposed by researchers at the University of Rochester.

Future Technology

In the future, QDs will be used to make highly efficient and powerful thermoelectric



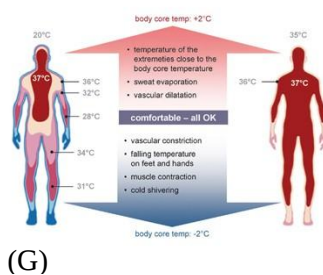
generators. Researchers at the University of Rochester have designed a nanoscale engine that uses QDs to facilitate the movement of electrons to produce energy in a thermoelectric system. This heat engine is made of five microscopic layers of silicon semiconductors

integrated with QDs, commonly referred to as the “swiss cheese sandwich.” In the diagram, two

layers of QDs (Layers 2 and 4) are surrounded by two cold electrodes (Layers 1 and 5) and a central warm electrode (Layer 3). The red central layer acts as a heat sink for the heat engine.

The top and bottom layers are both kept cold and provide the temperature differential which runs the engine. The engine’s overall efficiency is determined by the chemical potential energies of the QD layers; this is a combination of the materials that are used and the biasing that is placed on the device (further details can be found on our webpages). The efficiency^[3] of this new breed of Quantum BioEngine is as follows:

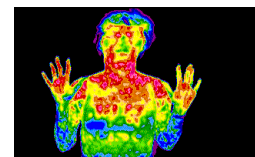
$$\eta = |\mu_l - \mu_r| / \Delta E$$



This equation divides the difference of the chemical potential energies of the two layers by the change in thermal energy.

Essentially, the electrons tunnel through the barrier away from Layer 1 (cold), picking up thermal kinetic energy from the hot

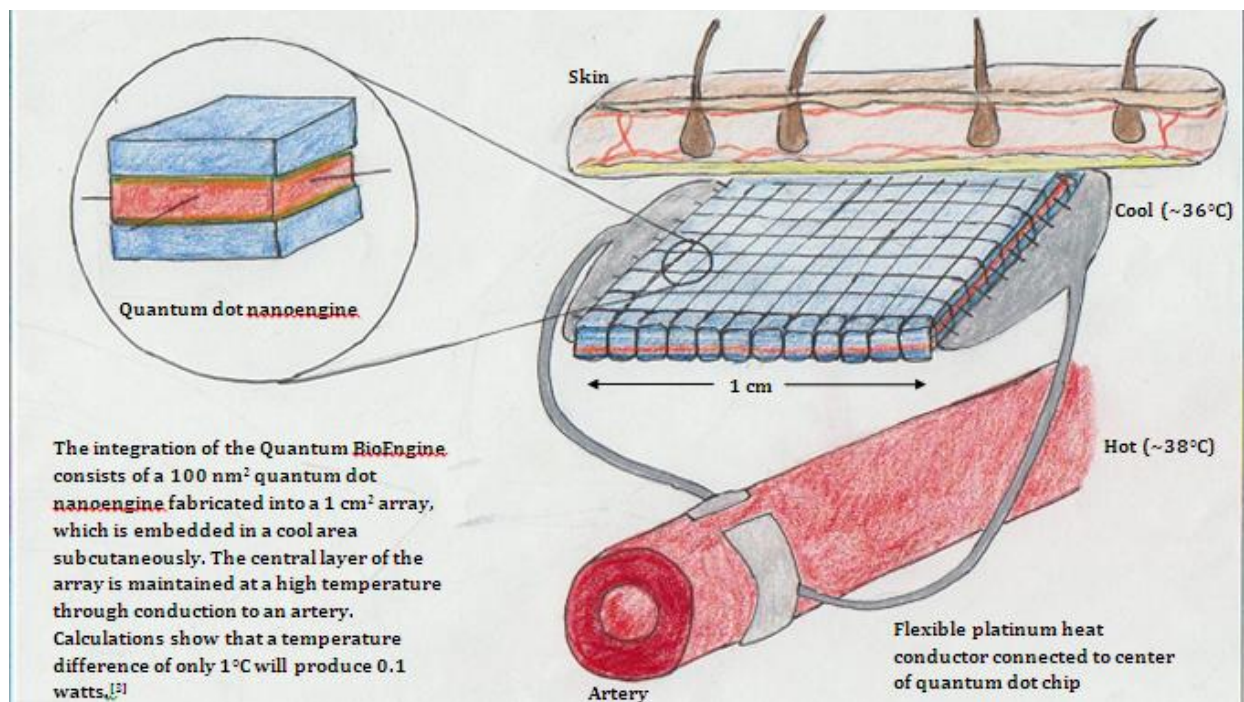
central layer (Layer 3), then tunnel again through the second barrier into Layer 5 (cold). The efficiencies are so pronounced that they are comparable to the amount of solar energy that falls on the surface of the earth. The solar constant is 1360 W/m², whereas a 1 cm² array of nanoengines



(H)

produces 1000 W/m^2 at a temperature differential of only 1°C . As it turns out, the human body has a natural temperature gradient as blood cools off toward the body's surface and extremities.

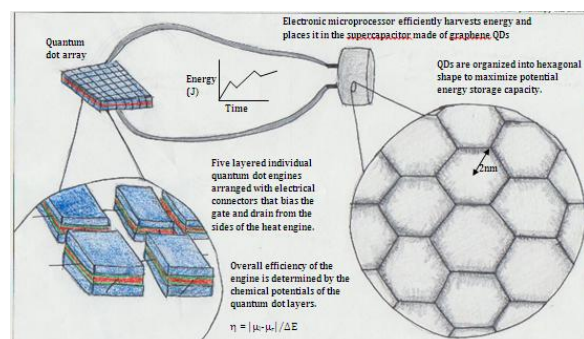
Our Quantum BioEngine of the future will exploit the slight temperature differences in the human body and use them to power the nanoengines. Our system, shown below, is comprised of a small nanoengine, approximately 100 nm^2 , fabricated into an array of about 1 cm^2 .



Illustrated by team

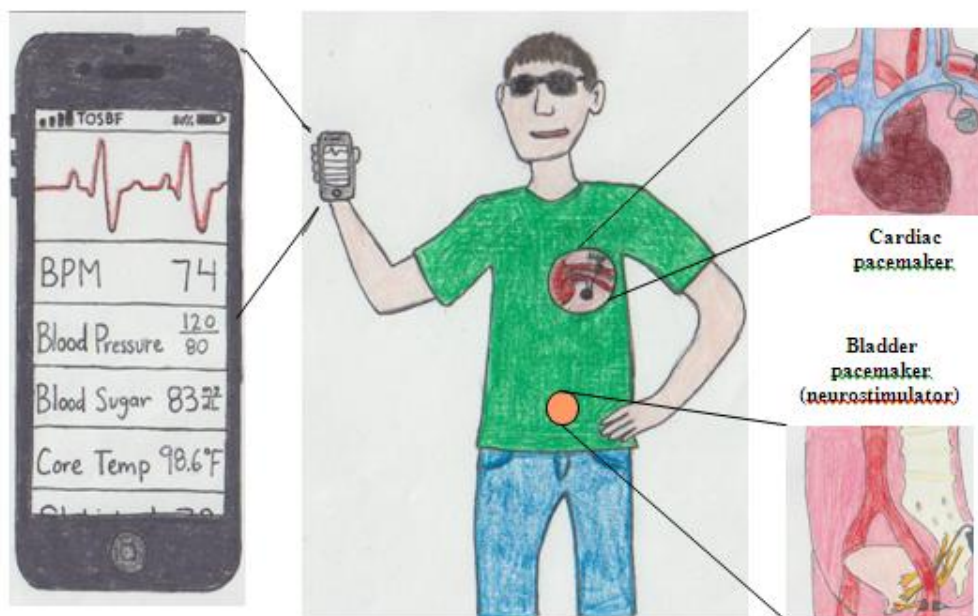
In order for our system to work, heat must be delivered to the central layer of the array. This is accomplished by wrapping flexible platinum wire around an artery located near the biomedical device, which conducts the heat up to the chip located in a cool subcutaneous location. The difference in temperature between the hot and cold layers will produce enough energy to power the implant.

Illustrated by team



While the array is able to provide power, there must be a way of storing energy. Recent work in micro-supercapacitors made from graphene quantum dots (GQDs) will allow for maximum power density and efficiency. The hexagonal shape of the GQDs in the supercapacitor allows for extremely high energy storage densities. In our system, the array is connected to an electronic control box, which includes a microprocessor that correctly biases the source and drain voltages to efficiently operate the nanoengine.

The entire system will be easily accessible through a wireless connection to a phone application, enabling users to constantly monitor the state of their body. Implantable biomedical devices such as pacemakers, defibrillators, neurostimulators, and future biosensors would all be powered by the Quantum BioEngine. The user would interface in real time through a wireless connection and a personal digital application.



Illustrated by team

Breakthroughs

In order for our Quantum BioEngine to work, five breakthroughs are needed.

Breakthrough #1: Fabrication

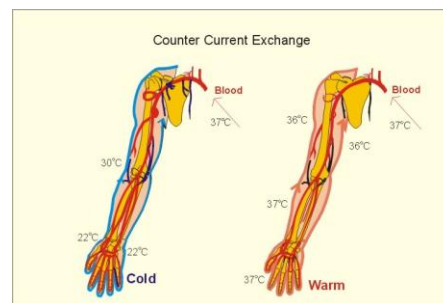
Nanostructures are extremely small—a quantum dot is typically only 2nm to 9nm across. Making a machine that can actually manufacture something so small is a technical feat, and is the primary factor holding us back from creating nanoengines on a large scale. However, some researchers have discovered that QDs can self-assemble, which means that they can be randomly placed rather than precisely located on the chip. This random placement has theoretically been shown to have no effect on the overall efficiency of the engine. A single nanoengine is just one task to complete, but a real array would involve hundreds of individual nanoengines, each one intertwined to the others with a central heat source connecting them all.

Breakthrough #2: Surgical Techniques

Our Quantum BioEngine requires interfacing to a human artery. Surgeons will need to be trained in techniques required to place the heat conductor around arteries in various parts of the body. As with pacemakers and other safe implantable devices, human testing will also be necessary before the mainstream integration of the system.

Breakthrough #3: Human Temperature Mapping

Currently, the exact temperatures or “microclimates” throughout the body have not been recorded accurately. A minor breakthrough in precision isotherm mapping of the human body would be needed.



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Breakthrough #4: QD Design

Some semiconducting materials can be cytotoxic. The choice of material for the nanoengines must be carefully engineered. Precisely tuning a QD to the exact band gap energy needed for efficient tunneling requires ongoing research—this could take many years and continued governmental or private funding. We also need a breakthrough in lobbying efforts to apportion the amount of money available toward this research.

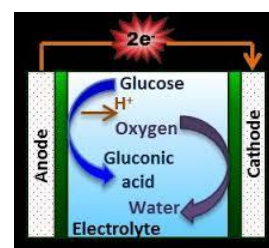
Breakthrough #5: Supercapacitors

Our Quantum BioEngine is able to produce high power, but still needs a way to store the energy that it harvests. The electronics to harvest the energy are not an issue; however, finding a device that is small enough to fit subcutaneously while still maintaining high power densities has not been demonstrated commercially yet. In current micro supercapacitors, researchers are struggling to align current materials into geometries that allow for the easiest ion diffusion rate. Right now, the energy density of the best QD graphene supercapacitor has been measured to 495 W per cm³. While far superior to electrolytic capacitors and lithium-ion batteries, the hurdle of effective geometric configuration of high energy density materials has kept, and will continue to keep researchers at bay until a breakthrough occurs.

Design Process

Our team became interested in energy harvesting techniques from a project that one of us started in research class. In this project, small amounts of energy would be generated by the swaying of a piezoelectric stalk in the wind. We knew that it was possible to electronically store micro bursts of energy, but we had an intense interest in medical applications, which led us to focus on harvesting energy within the body. The following are three rejected ideas during our design process.

Design 1 – Glucose: Originally, we thought using glucose would be ideal since our bodies naturally produce glucose as a source of energy. It is sustainable and used in all areas of the body. Many researchers have experimented with using a biofuel cell to conduct electrochemical energy;



(J)

however, when using the energy from the metabolic processes, carbon dioxide and oxygen are left in the body as byproducts. Another flaw in using glucose as the primary source of energy is that glucose levels fluctuate between different areas of the body. Ultimately, using glucose will not be the most efficient supply of power for an implantable device.

Design 2 – Kinetic Energy: After rejecting the glucose idea, we realized that there is a great amount of energy in the mechanical motion of the human body. Many researchers have looked at the flywheel battery—movement producing energy that is then stored in a supercapacitor. This would be ideal for individuals that are able to move easily on a daily basis to produce enough kinetic energy to power the device within their body. However, one of our team members

(K)



pointed out that this would be a challenge for their own grandmother who recently had a pacemaker implanted but has limited mobility. For individuals where movement is not as

accessible, this option is not a workable solution. Internal kinetic energy in a machine is also not accessible due to the potential size of a magnet generating electricity through a coil of wire.

Design 3 – Solar Energy: Because we disliked the second idea, one of our team members



(L)

suggested using implantable photovoltaic cells to harvest energy for medical devices. We thought we could put the solar cell near the skin where light could enter through the transparent surface. However, we all saw the fatal flaw—there would be no energy harvested during the night. Likely, the implantable device would need a constant stream of energy and having such a long period of time with little energy to harvest could possibly be detrimental to the device's purpose.

Final Design – Quantum Dots: After rejecting the use of photovoltaic cells, we approached our science teachers for more ideas. They showed us a paper about using QDs to harvest energy. Using temperature differences within the body to power a thermoelectric engine, QDs would best suit the requirements of the device. There will always be a slight difference in internal body temperature in order to collect energy.

Consequences

Like all new technologies, the Quantum BioEngine design requires a paradigm shift in thinking, which can bring about positive and negative consequences.

First, as a design requirement, the medical implants that it powers must be compatible with the amount of energy that it harvests. Complications could arise if the energy harvester serves a cardiovascular defibrillator and is required to give the patient a life-saving shock, possibly requiring more energy than the harvester can supply. Our design includes a supercapacitor to prevent this. However, if there was a technical failure, it could be life-threatening. Current batteries can also fail, so a positive of our design is that it has fewer parts to fail and is all solid state, without any chemical reactions.

Our Quantum BioEngine is a heat engine, and relies on a heat differential to operate. By pumping hot blood to the cool surface of the human body, this design could present negative physiological effects depending on the extremity of the temperature; if the cold side of the harvester became extremely cold, individuals could suffer nonfreezing injuries. However, our Quantum BioEngine is highly efficient at small differentials of temperature, negating this risk.

QD technology also poses a risk to human health. A 2006 study, “A Toxicologic Review of Quantum Dots,” suggests that while toxicity varies depending on the type of quantum dot used, QDs have the potential to be cytotoxic. Additionally, there is a risk that the QD materials could leak or leach into the body, though the health risks of this are currently unknown.

The convergence of QD, thermoelectric, and supercapacitor technology with energy-efficient medical implants will allow for maintenance-free medical devices; patients need not worry about battery replacement or invasive corrective procedures. Additionally, this system can be locally applied to power devices in various parts of the body.

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